

# Direct Solar Radiation :A Modelling Technique

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## ABSTRACT

A Direct Solar Radiation modelling technique was developed by the Department of Conservation to provide solar radiation data for the future modelling of biological activity on Kapiti Island, New Zealand. The technique used a Digital Elevation Model and Solar Radiation values to quantify the amount of Solar Radiation directly striking the surface of the island. The benefits of using this technique, instead of aspect, were assessed. GIS technology was used to determine shading and the angle at which Direct Solar Radiation strikes the earth. The seasonal variability in Direct Solar Radiation was assessed. Potential applications of this technique have been identified.

**Keywords and phrases:** spatial modelling, solar radiation, seasonal climate variation, GIS, digital elevation model, environmental gradient, aspect, topography

## 1.0 INTRODUCTION

### 1.1 The Project

The primary purpose of the project was to develop a technique to ascertain in a simple manner the quantity of solar radiation reaching every portion of a topographic surface, so that extremes of solar radiation could be identified. Solar radiation provides a continual energy input to the earth in the order of 170 billion megawatts. Incoming solar radiation is the primary driving force for Earth's physical, biological, and industrial systems (Fu & Rich 1999). This energy arrives in the wavelength range 0.3-10 $\mu$ m. The majority is received in the visible and infrared spectra (Gates 1965 cited in Barbour *et al.* 1980) but radiation in the range 0.4-0.7 $\mu$ m is the wavelength band absorbed by chlorophyll and therefore these wavelengths are active in the photosynthetic process (Barbour *et al.* 1980). Levels of solar radiation directly affect air, water and soil temperature, evaporation, ecosystem energy flows, and plant and animal growth. Traditionally, northerly aspect has been used as a surrogate for high solar radiation surfaces. However, in this project, aspect was considered to be an extremely crude measure of solar radiation, and an improved technique was sought.

Solar radiation data are needed to undertake ecological modelling of species and community distributions on Kapiti Island, an internationally important nature reserve. Solar radiation was seen as just one of many environmental forcing factors. In particular the modelling was intended to predict the sites favoured by *heliothermic* (sun-loving/sun-basking) lizards, and to assess the most suitable sites for the liberation of fauna.

The project started in 1997 when the Digital Elevation Model (DEM) for Kapiti Island was acquired, and we applied it to model the solstice solar radiation data. Since then comparison analyses have been undertaken to look at the seasonal variability of solar radiation, and how this technique improves upon using aspect alone as a measure of solar radiation. It is concluded that this technique gives more accuracy than the use of aspect alone, particularly in summer.

## 1.2 Context

A literature search was undertaken as part of Wildfire Risk Modelling Research in conjunction with the National Rural Fire Authority. Software application developments have been progressing in recent years. In 1994 a project in the Rio Grande River Basin developed a modelling technique that used incoming radiation and reflectance data to assess net solar radiation (Dubayah 1994). Also in 1994 the SOLARFLUX modelling technique was developed to provide full direct solar radiation and a limited diffuse radiation. It used ARC/INFO GRID hillshade for the shading component of direct solar radiation and specific programs for the other results (Rich *et al.* 1994). In 1997 a similar modelling technique was developed by Kumar *et al.* (1997) using ARC/INFO and GENAMAP. (Fu & Rich 1999). In 1999 Solar Analyst, an ArcView Extension, was developed to model direct and diffuse solar radiation modelling. It used the “upward-looking hemispherical viewshed... (fisheye)” approach. A similar application called TopoView was developed to work with ARC/INFO (Fu & Rich 1999).

Solar Analyst represents a cheap, practical solution to use in our ArcView environment, which is more accurate than the modelling technique described in this paper. However, the modelling technique in this paper provides a simple solution of minimal cost and complexity.

The recent release of ArcView Spatial Analyst 2 MODELBUILDER means that the flow diagram created by this modelling technique can be saved as a ModelBuilder template and rerun with different data.

## 2.0 ASSESSMENT OF POTENTIAL VARIABLES

This project has sought to ascertain whether aspect is an appropriate variable to identify high solar radiation surfaces, and has developed an appropriate and simple modelling technique using mainstream GIS technology.

First principles were used to identify the components that were most significant in determining surface solar radiation gradients.

### 2.1 Solar radiation transmission pathways

Solar radiation reaches the surface of the earth in 4 ways:

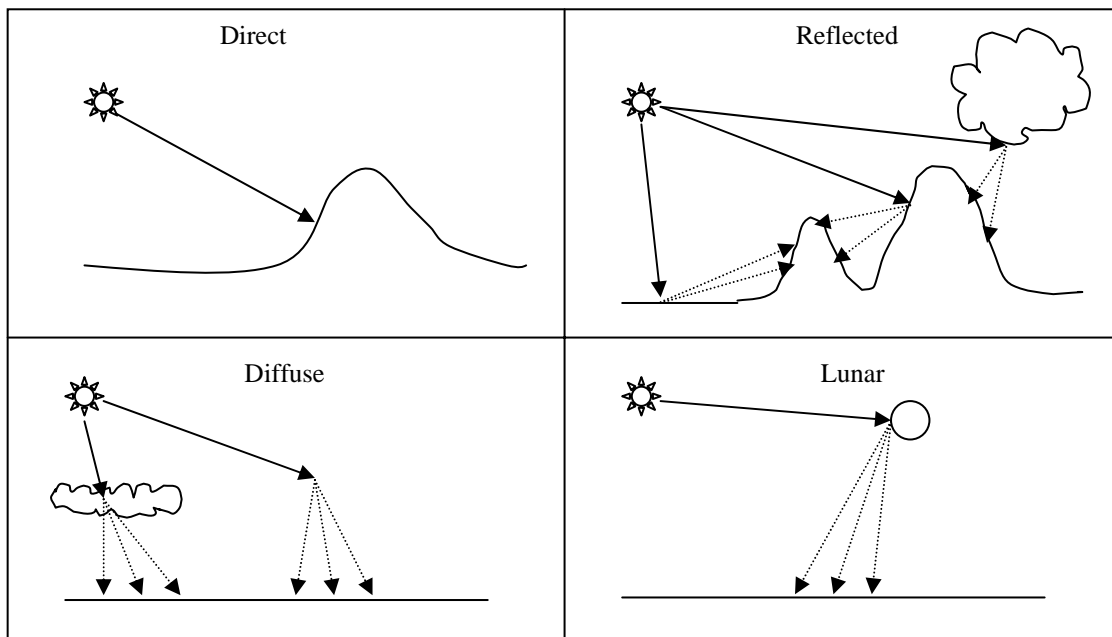


Figure 1: Solar radiation transmission paths

The quantity of solar radiation reaching any particular part of the surface of the earth is determined by the position of the moon, time of year, atmospheric diffusion, cloud cover, shape of the earth's surface, and reflectivity of surfaces.

### 2.1.1 Direct

Direct solar radiation is that which travels in a straight line from the sun to the earth's surface. Clear-sky day values are measured at many localities in New Zealand. To model this would require knowledge of intensities and direction at different times of the day.

### 2.1.2 Reflected

Direct solar radiation can be further reflected and dispersed across the surface of the earth or back into the atmosphere. To model this would require knowledge of surface reflectance and shape, and a means of modelling any dispersal. Albedo is a measure of how much radiation is reflected by a surface (Table 1). When the albedo is 1.0 all radiation is reflected; none is absorbed. When the albedo is 0.0 no radiation is reflected; it is all absorbed (Graves 1998). The albedo data in Table 1 shows that a significant proportion of direct solar radiation striking a surface is reflected, particularly from snow and clouds. What proportion of the reflected radiation strikes another surface is not known.

Surface	Albedo
Snow – fresh	0.80-0.95
Snow – old compacted/dirty	0.42-0.70
Ice – glacier	0.20-0.40
Seawater – calm, clear	0.03-0.29
Sand – windblown	0.20-0.45
Short grass(0.02 m)	0.26
Long grass(1.0 m)	0.16
Deciduous forest	0.15-0.20
Pine forest	0.14
Asphalt	0.05-0.20
Concrete	0.10-0.35
Clouds*	0.40-0.80

Table 1: Albedo of various surfaces(Yuri 1998)\*(Graves 1998)

In this project, reflected radiation was ignored because there is little known data on the albedo of New Zealand surfaces, particularly indigenous vegetation, and no known available tool or technique to model this source.

### 2.1.3 Diffuse

Diffuse radiation occurs when small particles and gas molecules diffuse part of the incoming solar radiation in random directions without any alteration in the wavelength of the electromagnetic energy.

Diffuse cloud radiation would require modelling clouds, which was considered impossible to do and would have been variable from day to day. It appears to only contribute a minor part to radiation energies from above the mid-visible through to the infrared spectrum, but can contribute up to 40% of the radiation energy from the mid-visible through to the mid-ultraviolet spectrum(Gates cited in Barbour *et al.* 1980). However, as the primary purpose was to model extremes of radiation, maximum extremes would only occur on cloudless days, and the minimum extreme would be zero so cloud would not influence that. So it is considered that diffuse cloud radiation can be ignored because it is not the main determinant of radiation energies, and the extremes of variability that we seek are unaffected by clouds and other atmospheric effects.

Diffuse radiation values are usually measured and expressed as vertical components. Data (Unpublished) was obtained from the National Institute of Water and Atmospheric Research Ltd (NIWA) and it was found that diffuse radiation was only up to 10-20% of the direct radiation value, and in the range 0-0.44MJ/m<sup>2</sup>/hour (Nichols 1997). As a generalisation diffuse radiation is uniform over a landscape in the vertical sense. The slope of any surface would reduce diffuse radiation intensities on that surface. This could be modelled by reducing the diffuse radiation values for a day by the cosine of the slope for the surface, which would favour flat sites.

In the end it was considered that diffuse radiation was of such low quantity and variability that it did not warrant modelling.

### 2.1.4 Lunar

Lunar radiation is considered to be irrelevant as it does not contribute towards any solar radiation maxima which occur during the day.

### 2.1.5 Summary

The clear-sky radiation transmission path that was most significant for variations and could be modelled, was Direct Solar Radiation. However, in particularly cloudy environments, such modelling would be inappropriate as most radiation would then be diffuse or reflected.

## 2.4 Elevation effects

Generally, higher elevations receive more solar radiation than lower elevations due to the solar beam travelling through less air mass (Fu & Rich 1999). As the Kapiti Island study site ranges in elevation from 0-521m there would be some variation due to elevation. Data indicates that the increase in zenith solar radiation due to elevation over this range would be 6% (Fu & Rich 1999). As the variation due to elevation would be on a relatively uniform gradient, this variation could be ignored for the Kapiti Island site.

## 3.0 THE MODELLING TECHNIQUE

Simple modelling of Direct Solar Radiation requires that the incoming radiation is known and that it can be applied to the surface of the earth at any point. The software available for modelling was ArcView 3.1 with Spatial Analyst 1.0. The elevation variations in incoming radiation were ignored.

### 3.1 Assessment of direct solar radiation in the atmosphere

Values for the quantity and direction of clear-sky direct solar radiation at Kapiti Island (Latitude  $-41.85$  Longitude  $-175.92$ ) were obtained from NIWA. They checked theoretical estimates against actual maximum direct solar radiation readings at a nearby local station to verify the values (Tables 2A & 2B).

Time (24hrs)	Solar Elevation (degrees)	Solar Azimuth (degrees)	Direct solar radiation (MJ/m <sup>2</sup> /hr) (0.29-4.0 $\mu$ m)
0530	7.7	114.7	0.50
0630	18.2	105.5	2.15
0730	29.2	96.4	2.70
0830	40.3	86.6	3.05
0930	51.3	74.6	3.25
1030	61.6	57.8	3.37
1130	69.4	30.0	3.43
1230	71.3	348.7	3.44
1330	65.8	313.5	3.40
1430	56.3	292.5	3.32
1530	45.6	278.7	3.16
1630	34.5	268.1	2.90
1730	23.4	258.8	2.46
1830	12.6	249.7	1.91
1930	2.5	240.3	0.09

Table 2A: Kapiti Island summer solstice direct solar radiation model parameters (Nichols 1997)

Time (24hrs)	Solar Elevation (degrees)	Solar Azimuth (degrees)	Direct solar radiation (MJ/m <sup>2</sup> /hr) (0.29-4.0μm)
0830	6.1	50.7	1.46
0930	14.0	39.2	1.98
1030	20.1	26.3	2.33
1130	23.8	12.0	2.53
1230	24.7	357.0	2.57
1330	22.6	342.1	2.48
1430	17.9	328.3	2.23
1530	11.1	316.0	1.90
1630	2.6	305.1	0.98

Table 2B: Kapiti Island winter solstice direct solar radiation model parameters (Nichols 1997)

### 3.2 Assessment of direct solar radiation striking the earth's surface

Once the quantity of solar radiation capable of striking the earth directly is known, then a technique is required to apply that to any specific surface area with its unique topographic form and surround.

#### 3.2.1 TOPOGRAPHIC factors

Solar radiation is dominated by topographic effects (Dubayah 1994). There are two topographic factors that govern how much direct solar radiation strikes a specific surface area:

- Shading occurs when a hill blocks any direct solar radiation from reaching a surface (Figure 2).

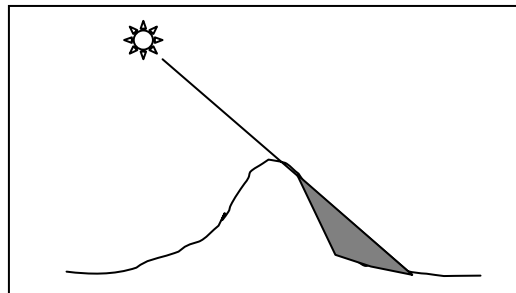


Figure 2: Shading

- Strike angle reduces the amount of direct solar radiation striking a surface (Figure 3). Maximum radiation occurs when the strike angle is perpendicular to the surface. Any reduction is by the value of the sine of the strike angle  $X$ .

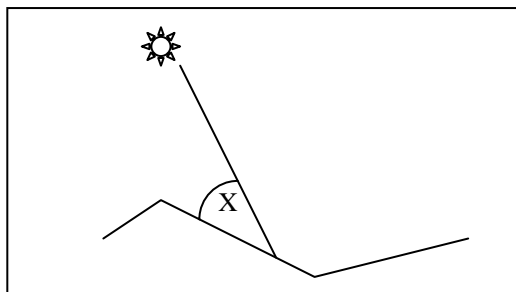


Figure 3: Strike angle

#### 3.2.2 APPLICATION of direct solar radiation to a surface

The shading and strike angle factors are used by the Hillshade function in both ARC/INFO and ArcView Spatial Analyst software applications developed by Environmental Systems Research Institute (ESRI). All that is required is to input the azimuth and elevation of the sun.

Hillshade values are produced in the range 0-254, where 0 is shaded and 254 is perpendicular to the solar radiation direction. There is a presumption that the values produced by Hillshade are the sine of the Strike Angle X. The azimuth and elevation for each hour are applied to the Digital Elevation Model (DEM) using Hillshade, then the results for each hour are summed.

When the direct solar radiation values are reduced in proportion to the hillshade value, the surface direct solar radiation value can be found.

The following parameters were used:

- IR = Incoming direct solar radiation (MJ/m<sup>2</sup>/hr) at hourly intervals
- HS = Hillshade value (range 0-254) at hourly intervals
- SRH = Surface Radiation/Hour (MJ/m<sup>2</sup>/hr) at hourly intervals
- SRD = Surface Radiation/Day (MJ/m<sup>2</sup>/day)

The following equations were used:

$$SRH = \left( \frac{HS}{254} \right) IR \quad (1)$$

The hourly value of direct solar radiation (SRH) for a surface is the product of the Hillshade factor and the Incoming Radiation.

$$SRD = \sum_1^n SRH \quad (2)$$

Total direct solar radiation (SRD) for a surface is the sum of the hourly direct solar radiation (SRH) for all hours when direct solar radiation occurs.

## 4.0 RESULTS

Kapiti Island, New Zealand was selected as a study site to apply the technique. This was because Digital Elevation Model (DEM) data were available at a 5m grid, and it is a nationally important nature reserve where the Department required increased understanding of the ecosystems, particularly for the restoration of biodiversity.

Initial processing was contracted out in 1997 to Terralink who used ARC/INFO GRID. Subsequent analysis of seasonal variation and aspect relevance was conducted in-house on ArcView Spatial Analyst 1.0.

The mapped data extracts presented below are for a small portion of the north-west shoreline, and are north orientated.

### 4.1 Summer/winter incoming direct solar radiation values

There is substantial variation in the intensity and duration of incoming direct solar radiation between season solstices (Figure 4).

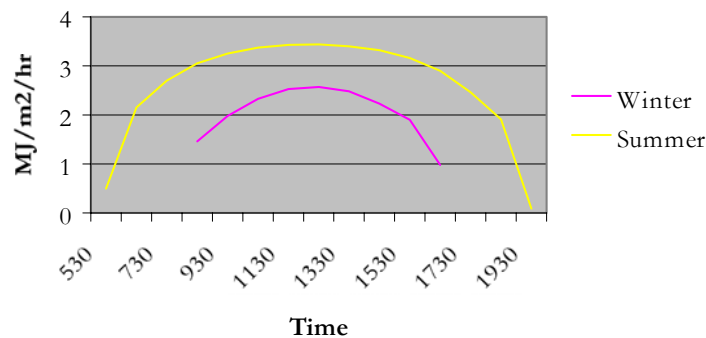


Figure 4: Diurnal variations of incoming direct solar radiation – Kapiti Island (Nichols 1997)

## 4.2 Surface summer/winter direct solar radiation

Daily surface direct solar radiation values for summer and winter solstices were derived (Figure 5).

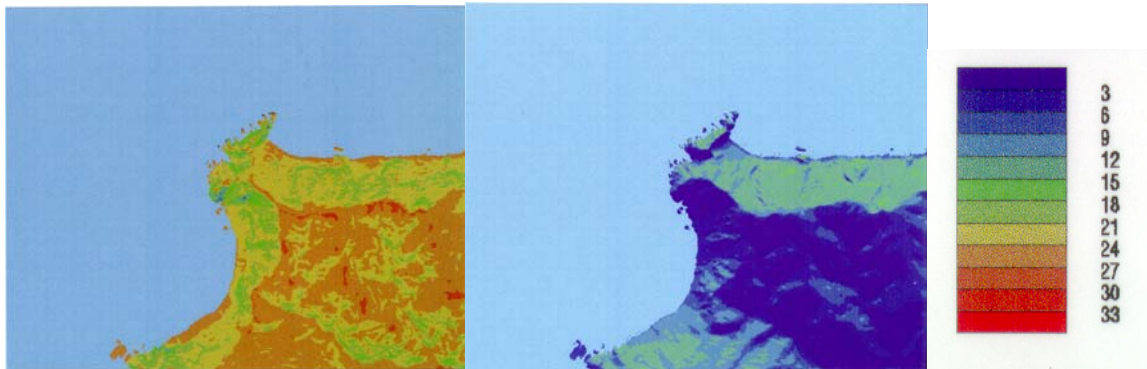


Figure 5: Summer and winter solstices direct solar radiation with key (MJ/m<sup>2</sup>/day)

The sunniest sites in summer are north facing and relatively flat (about 20-60 degrees of slope), and in winter are north facing at about perpendicular to the midday sun (about 65-70 degrees of slope), where they are not shaded to the north (330-25 degrees azimuth).

## 4.3 Variation between summer and winter direct solar radiation

A comparison was made between the summer and winter solstice direct solar radiation values to ascertain the seasonal variation (Figure 9).

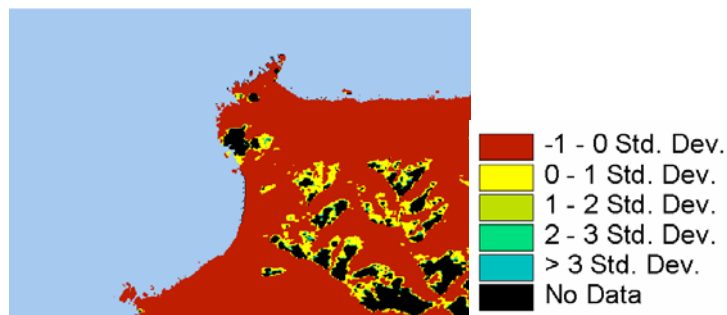


Figure 9: Summer/winter solstice direct solar radiation variation expressed as standard deviations

The shadiest winter sites receive no direct sun so they have a null value and produce “No data”. The results show that steep south facing slopes have the greatest seasonal variation (i.e. 2-3 standard deviations), while the most stable are north facing and optimised for the winter solstice sun.

Some sites were found to be warmer in the winter than in the summer, but only by about 5%. These were typically shade-free north facing slopes with a slope of about 65 degrees.

## 4.4 Comparison between aspect and surface summer/winter solstices direct solar radiation

Aspect was derived from the DEM using 8 sectors (Figure 6).

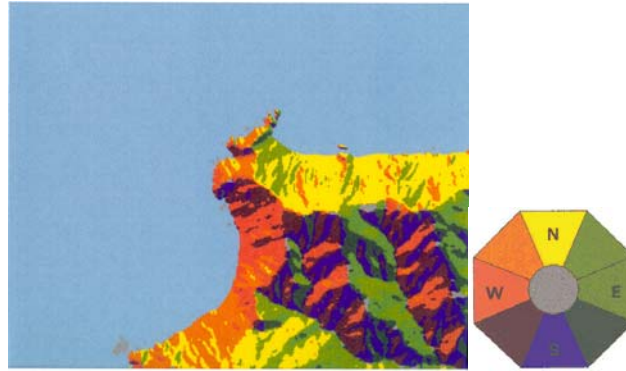


Figure 6: Aspect with key

Typically sites with the most sun are considered to be north facing. Comparison was made at 770,000 cells with the summer/winter daily direct solar radiation values referred to in Figure 5 (Figure 7).

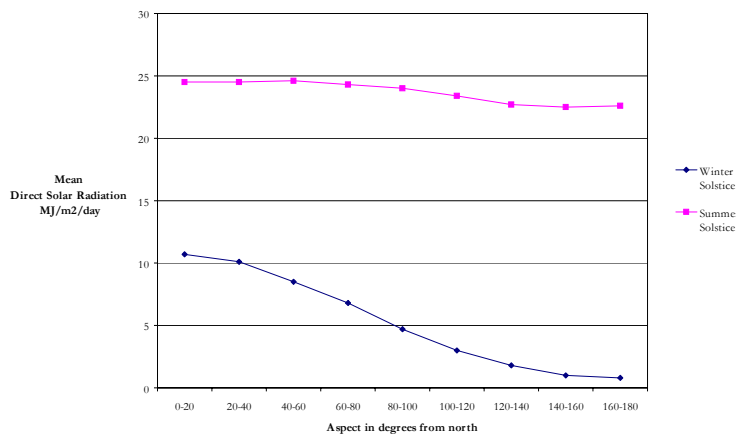


Figure 7: Mean direct solar radiation compared with aspect for solstices

There was found to be a reasonable site correlation between north facing aspect and the higher midwinter values in hilly country. There is no such site correlation with midsummer values, where high value sites are generally of any aspect, and highest in the aspect range between 0 and 60 degrees from north.

#### 4.5 Regional assessment

Subsequently the technique was used by Wellington Regional Council to assist in the assessment of wildfire hazard by way of multivariate analysis using ARC/INFO GRID. A summer solstice direct solar radiation dataset was created using the incoming direct solar radiation values for Kapiti Island as it was at a similar latitude (Figure 8).

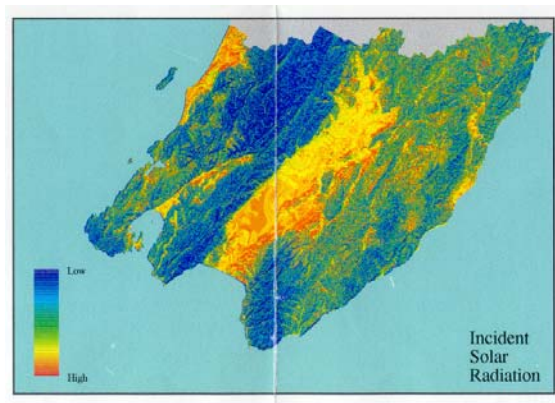


Figure 8: Wellington Region – Direct Solar Radiation, summer solstice(Forne 1998)

The accompanying report considered that it was an improvement when solar radiation was modelled rather than using a crude four-category aspect scoring (Forme 1998). It was found that flatter sites received the most direct solar radiation.

## **5.0 CONCLUSIONS**

Direct Solar Radiation modelling using the Hillshade function provides a general technique to assess variation in solar radiation at a local and regional scale, and between seasons. This technique provides improved results over using the aspect of a surface to indicate highest solar radiation quantities striking a surface. Aspect has been shown to be inappropriate as a measure of solar exposure, particularly in summer when the sun is much higher in the sky.

There are several sophisticated solar radiation modelling software applications available. They require resources that are not currently available in the Department's GIS environment, and demand complex and expensive data inputs. The Direct Solar Radiation modelling technique is simple to use and indicates the dominant solar radiation with a minimum of inputs and GIS resources. Use of the results in the real world has validated the technique, and shown its ability to finely distinguish solar gradients at the local and regional scale. International software application development is now leading to more sophisticated modelling techniques becoming available.

## **6.0 POTENTIAL APPLICATIONS**

It is considered that this technique can be applied in a number of other applications:

- Urban Real Estate – To verify claims of “all day sun”
- Health planning – To avoid siting residential properties and community facilities in unhealthy sites, or to compare health statistics with the shadiness of sites
- Species growth prediction – weeds and agriculture and ecology. To identify sites that favour particular species or communities based on minima/maxima and seasonal variation
- Ecological biogeography – To explain the distribution of species and communities
- Pre-historic Maori garden site prediction – To identify sites that receive the warming rays in spring to establish kumera for the long growing season required
- Ski-slope snow loss – To predict areas where snow will be lost due to the sun. Typically, predictions have used aspect, while ignoring slope, shading and solar radiation strike angles
- Wildfire risk prediction – To predict in dry and clear-sky conditions, sites with flammable vegetation are most likely to dry out and become a fire risk
- Biodiversity restoration – To identify appropriate sites, and organisms suitable for these sites

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